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RESEARCH & EDUCATION IN AIRCRAFT DESIGN
WARSAW, POLAND | 6-8 NOVEMBER 2024

UTILIZATION OF TOPOLOGY OPTIMIZATION AND GENERATIVE DESIGN FOR DRONE FRAME OPTIMIZATION

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Abstract

This study presents the process of optimizing a DJI F450 quadcopter using two optimization methods: topology optimization and generative design. The goal was to improve the overall performance of the unmanned aerial vehicle by altering its geometry and comparing the use of different materials. The primary objective was to reduce the mass of the original DJI F450 frame by 10%.

To enable optimization using both methods, modifications were made to the original DJI F450 frame. A total of five cases were prepared: one for the original DJI F450 frame, three for topology optimization, and one for generative design. Appropriate constraints were applied to simulate the real-world forces acting on the drone during flight.

The various optimized frame designs underwent static analysis to evaluate stress, strain, displacement, and safety factors. These results were then compared with those of the original DJI F450 frame, which also underwent static analysis. The comparison focused on the performance and mass of the original frame versus the optimized versions.

The results revealed that the optimized DJI F450 frames could achieve improved performance under flight-like load conditions, with reduced mass and comparable stress and strain levels. This demonstrates that engineering optimization, combined with additive manufacturing, can yield superior results, producing lighter, more capable organic structures compared to traditional frames.

Keywords: Optimization, Topology Optimization, Generative Design, Drone, DJI F450

1. Introduction

Interest in unmanned aerial vehicles (UAVs) began almost two centuries ago, but in recent times it has grown rapidly due to advancements in technology and new materials. UAVs provide significant capabilities without the need to risk human health and can be safely operated from remote locations. New lightweight materials offer even greater potential to optimize drone designs, and optimization tools help maximize performance while minimizing the size of the structure [1].

Two optimization tools that can be used for optimizing drone design are topology optimization and generative design.

Topology optimization is a computational design approach used in engineering and manufacturing to optimize the material distribution within a given design space, aiming to achieve the best structural performance while minimizing material usage. By iterative removing unnecessary material from the initial design and redistributing it according to specified load conditions and constraints, topology optimization generates intricate and often organic-looking structures that are both lightweight and structurally efficient. This method leverages mathematical algorithms to refine designs, resulting in innovative solutions for various applications, including aerospace, automotive, and product design [2].

Generative design is an iterative design process that involves using algorithms and computational power to explore numerous design possibilities based on specified constraints and goals. By inputting design parameters such as load requirements, material properties, and manufacturing constraints into software, generative design algorithms autonomously generates, evaluates, and evolves multiple design outputs. These iterations often produce complex and optimized solutions that might not conceive of initially. Generative design enables engineers and designers to explore a wide range of design alternatives efficiently, helping to uncover innovative and efficient solutions across various industries, including architecture, product design, aerospace and automotive.

Both methods are applicable for optimizing aircraft structures. Topological optimization was used, among other things, to modify the geometry in order to reduce the mass of a MALE-class UAV fuselage [3] and the control system frame for a missile [4]. In other cases, topological optimization has enabled a significant reduction (from 30% to 50%) in the mass of a self-designed drone while maintaining similar strength parameters [5,6]. In other studies, topological optimization was applied to improve locally concentrated stresses and large deformations around the front and rear sections of the engine support member for a cargo octocopter drone [7].

Generative design was also utilized for designing the drone frame and comparing it to the DJI F450 (similar to the studies presented in this article) [8]. In other studies, generative design was used to create a comprehensive design of a 6-axis quadcopter drone [9].

It can thus be observed that the application of topological optimization and generative design is very versatile and can be used both for modifying existing structures and for creating entirely new ones. Topological optimization is also applicable for improving sensitive areas of a structure, particularly in the context of performing non-standard operations and tasks.

It should also be emphasized that the use of topology optimization and generative design goes hand in hand with the development of the 3D printing industry, which enables the production of lightweight, complex structures with optimal performance, including those designed to withstand high loads [10,11] and with alternative fillings [12,13].

The aim of this study is to utilize both methods to optimize the same structure in order to analyze and compare the results obtained.

2. Description of the method and conditions

2.1 Background and objective

The objective of this paper is to optimize the frame of a selected drone to enhance overall performance by modifying its geometry and materials. The target is to achieve a 10% reduction in the drone's frame mass. The chosen drone for this study is the DJI F450, a popular multi-rotor model designed for aerial photography, videography, and recreational flying. Renowned for its versatility and user-friendly design, the F450 features a robust frame made from lightweight materials, providing agility and manoeuvrability. It typically houses a flight controller, electronic speed controllers (ESCs), and motors, enabling smooth flight and stability. The F450 is often used as a customizable platform, allowing users to integrate various accessories such as cameras, gimbals, and GPS modules to expand its functionality. Its modular design and compatibility with DJI’s flight control systems make the F450 a preferred choice for both novice and experienced drone enthusiasts engaging in aerial activities.

2.2 DJI F450 frame material and mass properties

The DJI F450, due to its simple design, is constructed from only two materials. The two center plates, which hold the entire structure and electronic components together, are made of PCB. The drone's arms are made from PA66-GF [14]. Some of the properties of these materials are presented in Table 1.

Table 1 – Material properties

Parameter	PCB	PA66-GF
Density	$1.944\,\frac{\mathrm{g}}{\mathrm{cm}^3}$	$1.34\,\frac{\mathrm{g}}{\mathrm{cm}^3}$
Young modulus	$24370\ \mathrm{MPa}$	$5500\ \mathrm{MPa}$
Poisson ratio	0.1649	0.34
Bulk modulus	$12121\ \mathrm{MPa}$	$5729.2\ \mathrm{MPa}$
Shear modulus	$10460\ \mathrm{MPa}$	$2052.2\ \mathrm{MPa}$

Necessary data which were needed in this thesis are specific masses of each of the components. For optimization only structural parts are needed that is why masses of other components such as motors and electronics will be neglected. Their impact on the flying characteristics have been included in the thrust generated by the drone itself with all of the components inside. It has to be stated that full DJI F450 drone frame consists of: plate top, plate bottom, 4 arms. Masses of each component you can find in Table 2. In Figure 1 model of frame [15] before optimization is presented.

Table 2 – Components masses

Component	mass	pieces
Plate top	$0.04487\ \mathrm{kg}$	1
Plate bottom	$0.06688\ \mathrm{kg}$	1
Arm	$0.05533\ \mathrm{kg}$	4
SUM	$0.333\ \mathrm{kg}$	6

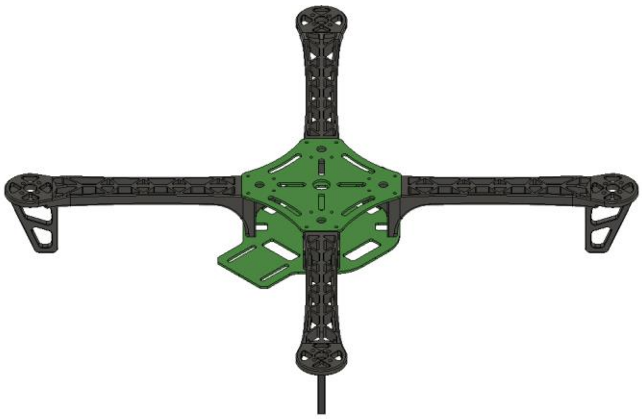


Figure 1 – DJI F450 001 initial reference frame model before optimization [15]

Additionally to perform any optimization of the drone structure thrust data is required. It has been found out that the total thrust generated by basic DJI F450 drone is 40 N [16].

2.3 Model preparation for topology optimization

The reference model of the DJI F450 frame was modified to enable accurate results from topology optimization, recognizing that this method removes material rather than adds it. For this purpose, four cases were prepared: one representing the original F450 frame (DJI F450 001) and three modified models (DJI F450 002, DJI F450 003, DJI F450 004) with varying amounts of material added. All cases are presented below, with details about the models provided in Table 3. Modified models are presented in Figure 2

Table 3 – Models parameters

Parameter	DJI F450 001	DJI F450 002	DJI F450 003	DJI F450 004
Mass	0.333 kg	0.448 kg	2.144 kg	11.231 kg
Volume	203 cm^3	287 cm^3	1525 cm^3	8158 cm^3

a) b) c)

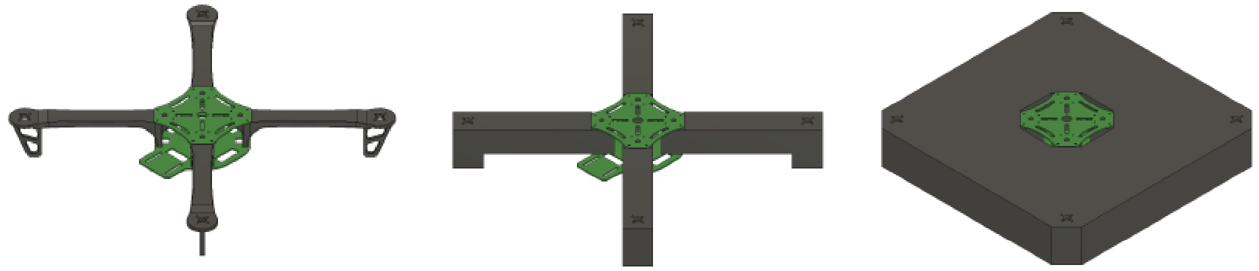


Figure 2 – Modified models before optimization: a) DJI F450 002, b) DJI F450 003, c) DJI F450 004

2.4 Static analysis before topology optimization

This analysis was performed to see values of displacement, stress and strain on the initial models to have a perspective and way of comparing this results to those which will be obtained after the optimization and post processing. Results you can find in Figures 3-6.

a) b) c)

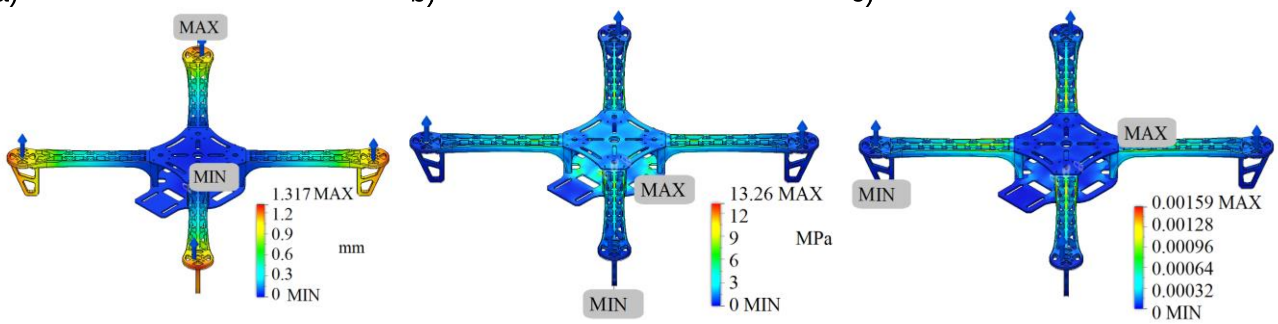


Figure 3 – Results for DJI F450 001: a) displacement, b) stress distribution, c) strain distribution

a) b) c)

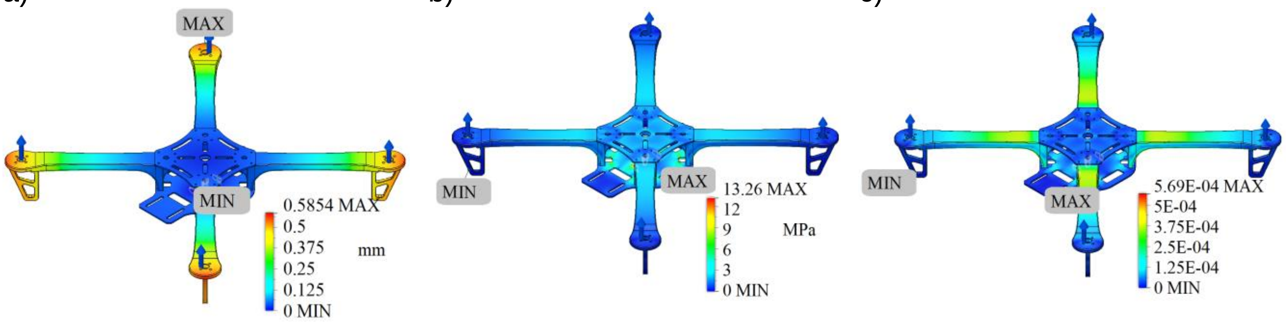


Figure 4 – Results for DJI F450 002: a) displacement, b) stress distribution, c) strain distribution

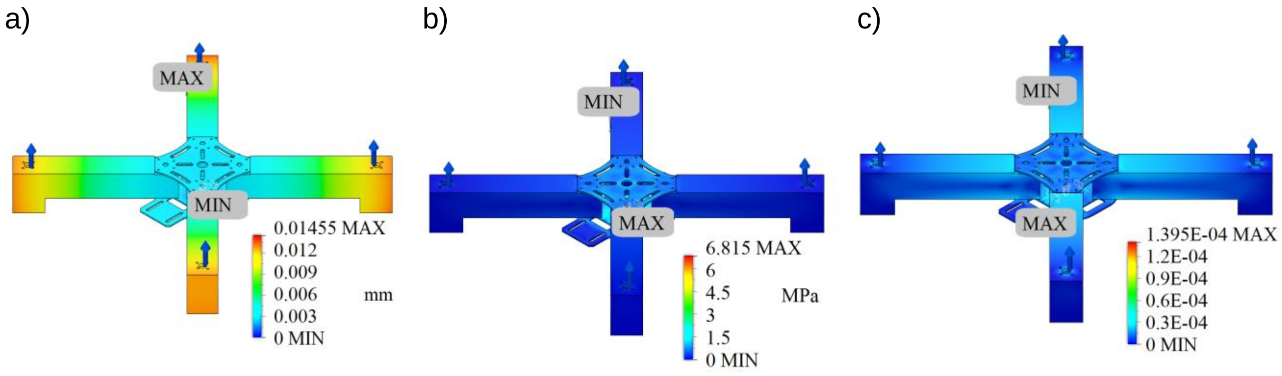


Figure 5 – Results for DJI F450 003: a) displacement, b) stress distribution, c) strain distribution

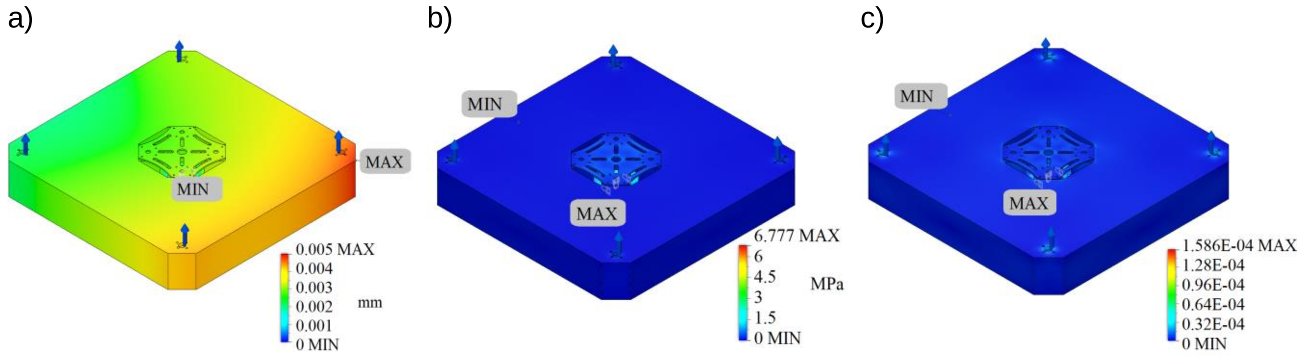


Figure 6 – Results for DJI F450 004: a) displacement, b) stress distribution, c) strain distribution

In the DJI F450 004 case, for unknown reasons, the distribution of the displacement along the frame is neither even nor symmetrical, despite the fact that all of the constraints and forces have been applied properly. However, based on the obtained results and due to the added material to the frame, the maximum displacement has a low value of just 0.005 mm (Figure 5a). The above disturbance may be the result of numerical errors. In Table 4 you can find a summary of the analyses.

Table 4 – Results of first static analysis

Parameter	DJI F450 001	DJI F450 002	DJI F450 003	DJI F450 004
Maximum Displacement	1.317 mm	0.5854 mm	0.01455 mm	0.005 mm
Equivalent Stress	13.26 MPa	13.26 MPa	6.815 MPa	6.777 MPa
Equivalent Elastic Strain	$15.9 \cdot 10^{-4}$	$5.69 \cdot 10^{-4}$	$1.395 \cdot 10^{-4}$	$1.586 \cdot 10^{-4}$

2.5 Settings for topology optimization

In order to perform this simulation, the Shape Optimization feature provided by Autodesk Fusion 360 was used. The following settings were applied to the analyzed model:

- **target body:** the arm of the DJI F450, as this was the element considered in the optimization.
- **preserve region:** a cylinder with a radius of 12 mm and a height of 5 mm was added to the engine mounting point at the end of the arms to preserve this part, allowing the engines to be re-mounted on the drone.
- **constraints:** as in the static analysis, the lower plate was fixed.
- **loads:** forces were applied at the engine mounting points, in accordance with the thrust generated by the engines, as done previously.
- **mesh:** the mesh model size was set to 3%.

Knowing the mass of the model for each case, two boundary masses as percentage of initial model were determined: one for maximum reduction (assuming the model's mass will be 75% of the reference model) and one for minimum reduction (assuming the model's mass will remain 100% of the reference model). Calculation results are presented in Table 5.

Table 5 – Requirements for optimization

Mass - Percentage	*DJI F450 001 (reference)*	DJI F450 002	DJI F450 003	DJI F450 004
of reference model	*100%*	152%	918%	5009%
for maximum reduction	*75%*	49.33%	8.155%	1.49%
for minimum reduction	*100%*	65.77%	10.88%	1.99%

Using the calculations provided in Table 6, appropriate simulations were conducted to evaluate the shapes generated by the program for three cases of mass reduction. The final optimized geometry was selected based on the range of minimum and maximum mass reduction. Models with the applied settings are presented in Figure 7.

In the case of topological optimization, it was assumed to keep the same materials as in the reference model 001.

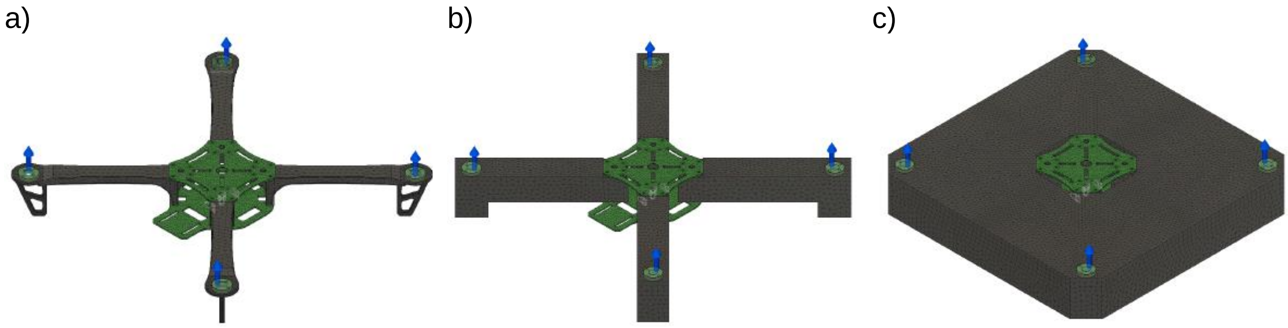


Figure 7 – Shape optimization setup: a) DJI F450 002, b) DJI F450 003, c) DJI F450 004

2.6 Data and conditions for Generative Design

To perform Generative Design analysis, the Autodesk Fusion 360 Generative Design module was used.

In order to perform such an analysis, the following parameters have to be set:

- **preserve geometry:** refers to the parts of the model that are intended to remain unchanged and be connected using generative design. As shown in Figure 8, both plates of the drone were selected, along with a cylindrical area with a radius of 12 mm and a height of 5 mm to retain the engine mounting points (similar to previous topology optimization).
- **obstacle geometry:** refers to areas where the generative design algorithm should not generate any material, keeping the space clear. In this model, the electronics compartment between the two plates has been defined as an obstacle, as well as the motor mounting points with screw locations.
- **structural constrains and structural loads:** similar to the previously described setup for topology optimization, the lower plate was fixed, and force was applied to the engine mounting points according to the thrust provided by the drone.
- **design criteria and manufacturing methods:** for this particular case, the design criteria were set appropriately:
    - **material:** PA66-GF, PA12 - nylon and ABS plastic;
    - **objective:** minimize mass by setting safety factor to more than 1.5;

- **manufacturing methods**: additive in all orientations (X+, X-, Y+, Y-, Z+ and Z-) and unrestricted.

Parameters set in Generative Design for model DJI F450 001 are presented in Figure 8.

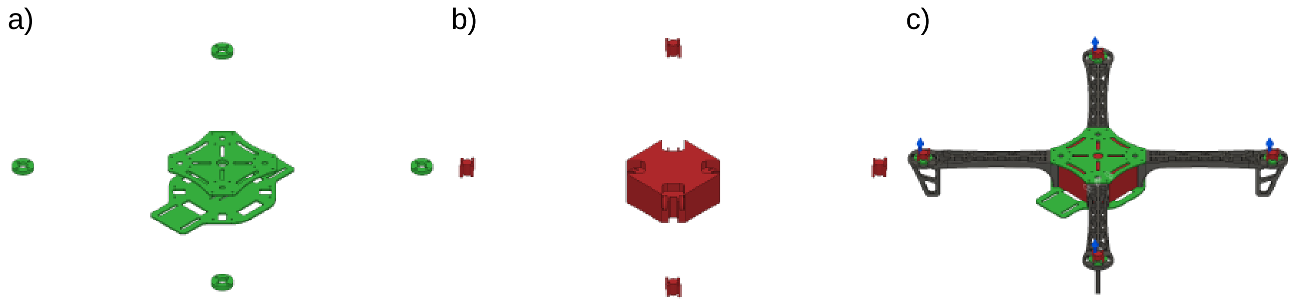


Figure 8 – Parameters in Generative design: a) preserve geometry, b) obstacle geometry, c) generative setup

3. Results

3.1 Topology optimization output

After performing a topology optimization, a graphical representation is presented, showcasing the optimized shape of the drone's arm with the target mass reduced. It was possible to adjust the amount of reduced material, which slightly changed the results. Different colours indicate which material will be reduced first (green and yellow) and which will be removed later if further mass reduction is necessary.

In the DJI F450 002 (Figure 9), it can be seen that the optimization area was constrained by the initial model, so the algorithm did not have to remove a significant amount of material. Most of the material was removed from the sides near the tip of the arm, leaving nearly the original amount at the root. Surprisingly, for an unknown reason, the design was not symmetrical, despite the initial model being symmetrical and the force being applied along the circumference of the line of symmetry.

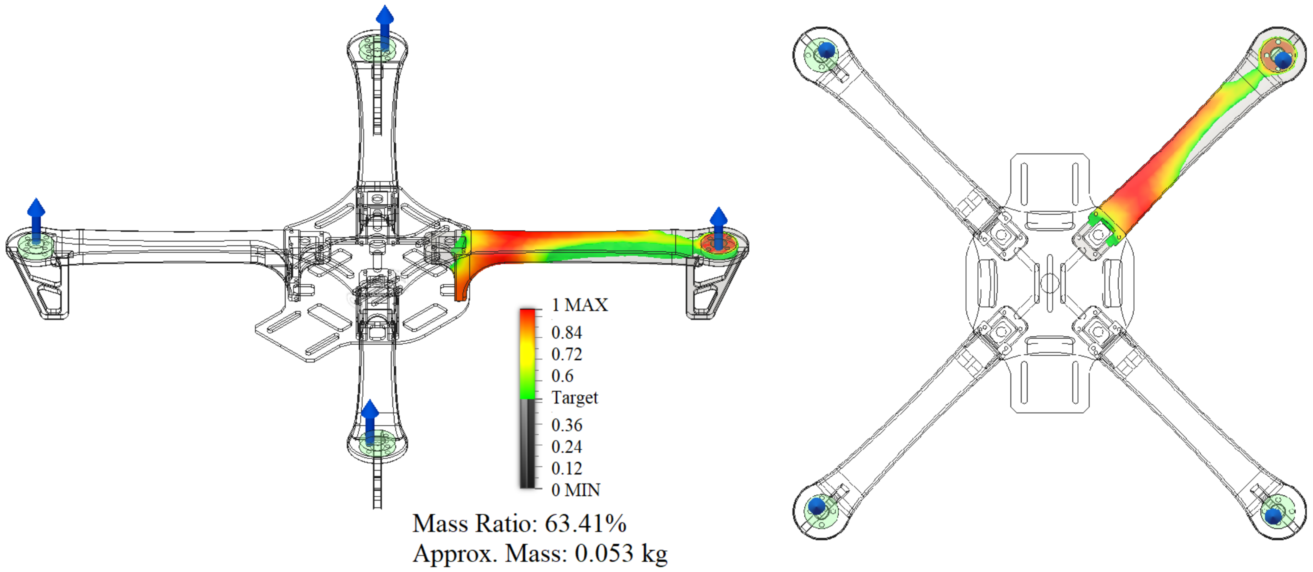


Figure 9 – DJI F450 002 geometry after optimization – side and top view

Looking at the second model, DJI F450 003 (Figure 10), the algorithm had much more material available to work with. The shape was similar to the first result, but the algorithm attempted to generate additional support from the bottom plate to the engine mount. However, for an unknown reason, it did not connect to the material supporting the engine mount, so this was not taken into consideration. Similar to the previous result, the arm was not symmetrical, despite the same forces and constraints being applied. This optimized arm is much thinner compared to the original model and the other results.

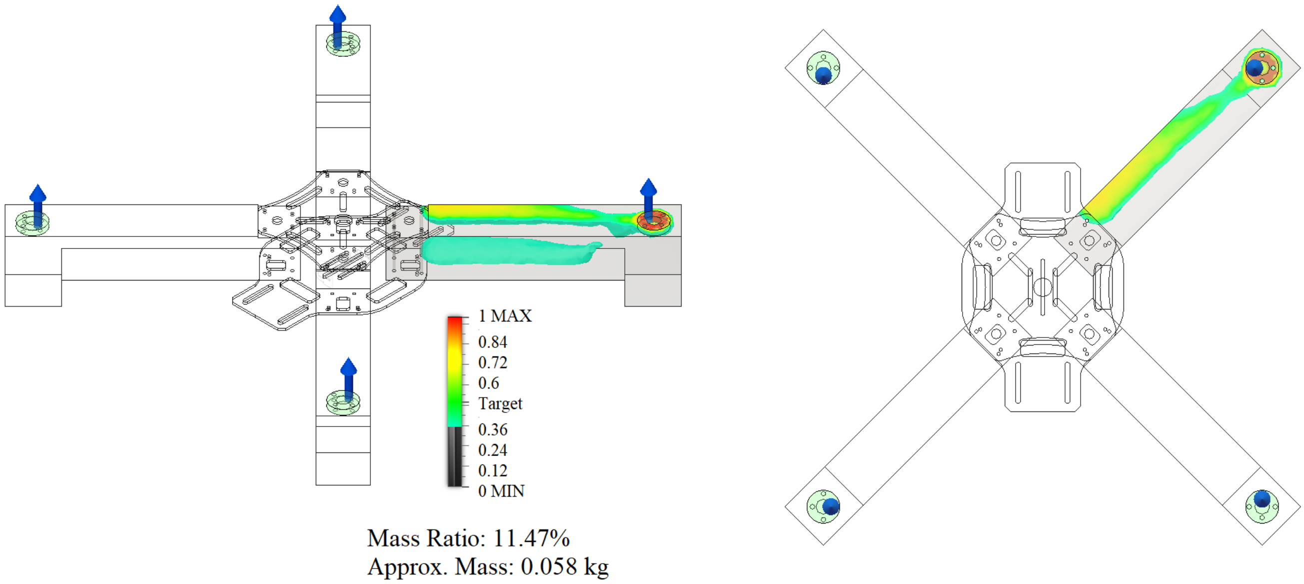


Figure 10 – DJI F450 003 geometry after optimization – side and top view

The last case DJI F450 004 (Figure 11) had the maximum possible amount of material to work with. The resulting design retained more material at the root of the arm, including all of the mounting points. The arm did not reach the engine mount, but this was overlooked because it provides a suggestion of how the arm should look, which will need to be manually modified in the model itself. This time, the arm was generated from one side and then extended in a straight line toward the engine mount.

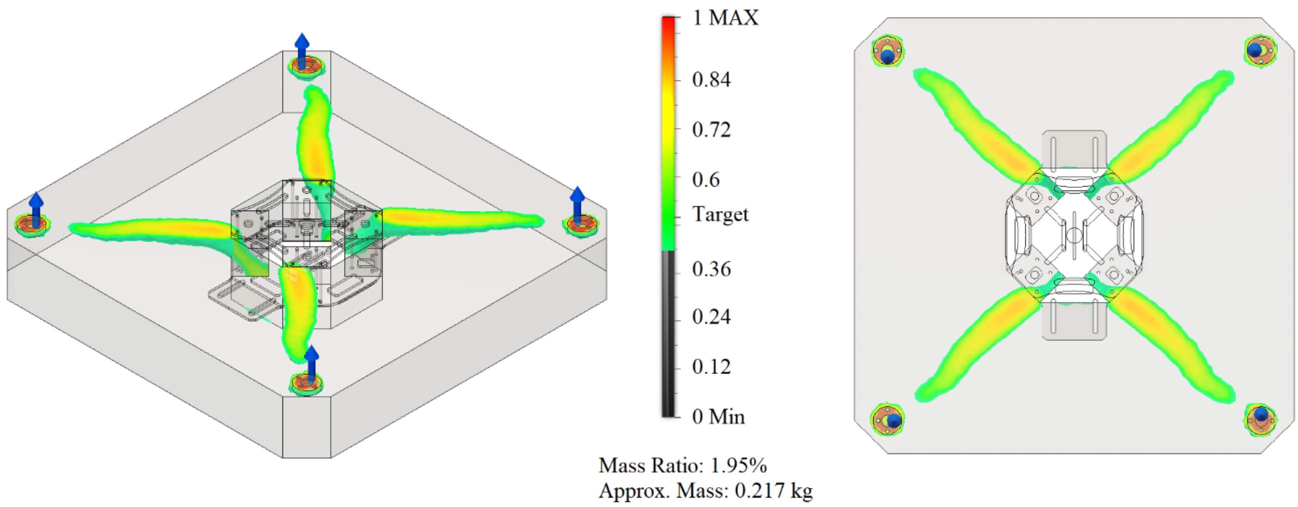


Figure 11 – DJI F450 004 geometry after optimization – side and top view

3.2 Static analysis after topology optimization

The best results obtained from shape optimizations were evaluated using the same settings as the reference DJI F450 001 model. This comparison will provide valuable insight into the differences between the original frame and the newly designed, lighter frame. It will allow for an analysis of stress, strain, and deflection using the same materials as the original frame. The obtained results serve as a guide for modifying the model to achieve similar performance while reducing the weight of the drone's frame. Each model was manually modified based on the presented results.

The optimized model DJI F450 002 (Figure 12a) underwent another round of static analysis, with the results presented below. The new frame shows a reduction of 37 grams, which is over 11% of the total mass. The maximum displacement decreased by 35% compared to the original frame (Figure 12b). As predicted, the maximum displacement occurs near the engine mounts. The highest stress in the model is located at the bottom plate where the constraint was applied, and the stress value remains nearly the same as in the original model (Figure 12c). In terms of strain, the maximum value is located in the middle of the arm. It is lower than in the reference model, indicating better material performance under load (Figure 12d).

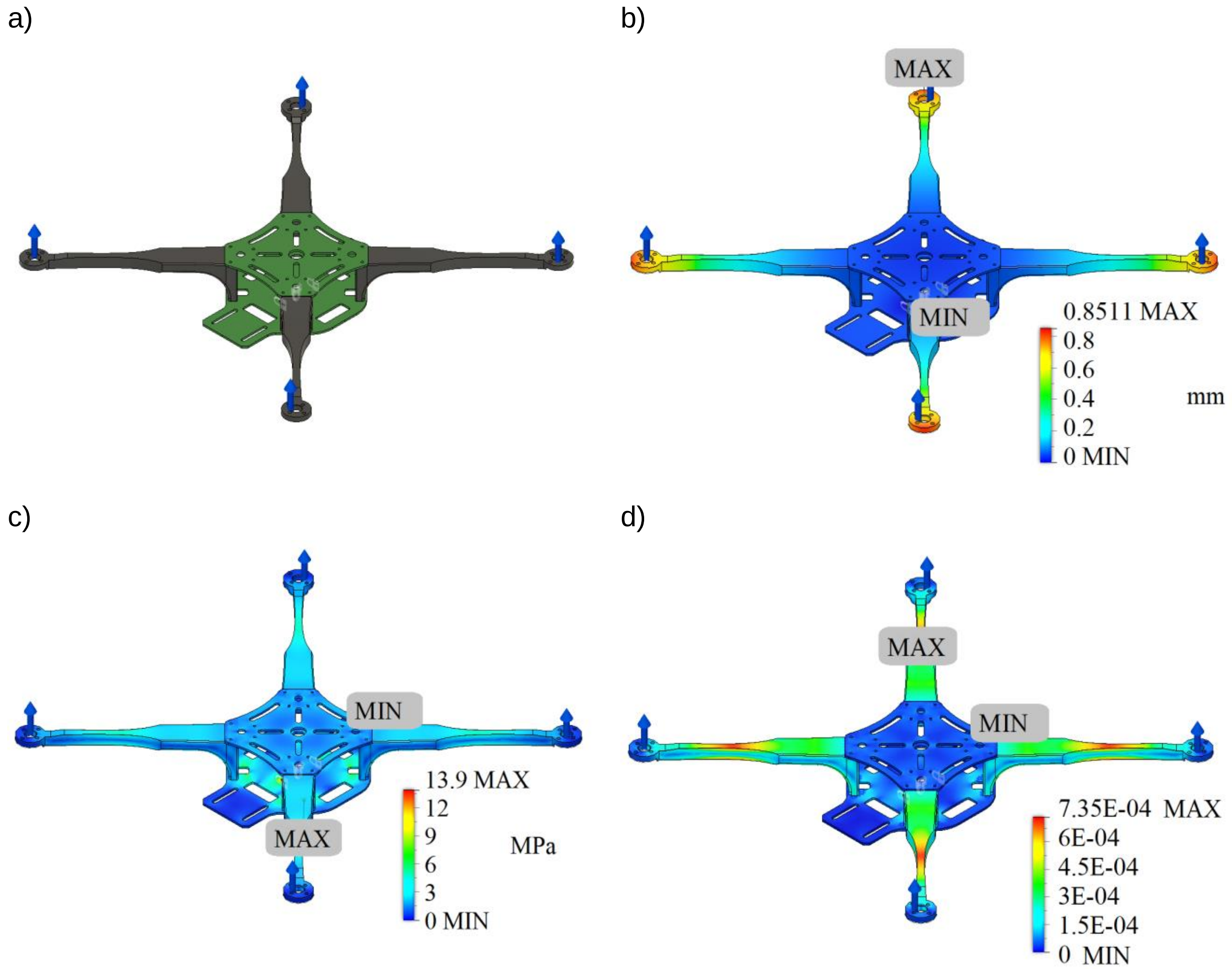


Figure 12 – Results for DJI F450 002 after optimization: a) second static analysis setup b) total displacement, c) stress distribution, d) strain distribution

In the case of the DJI F450 003 (Figure 13a), the new arms, based on the topology optimization output, unfortunately increased the frame's mass to 1 kg, which cannot be considered a successful result. The additional material reduced the maximum deformation near the engine mounts, as well as the strain in the arms (Figures 13b and 13c). However, the maximum stress, which again appears in the bottom plate, remains the same as in the reference DJI F450 frame (Figure 13d).

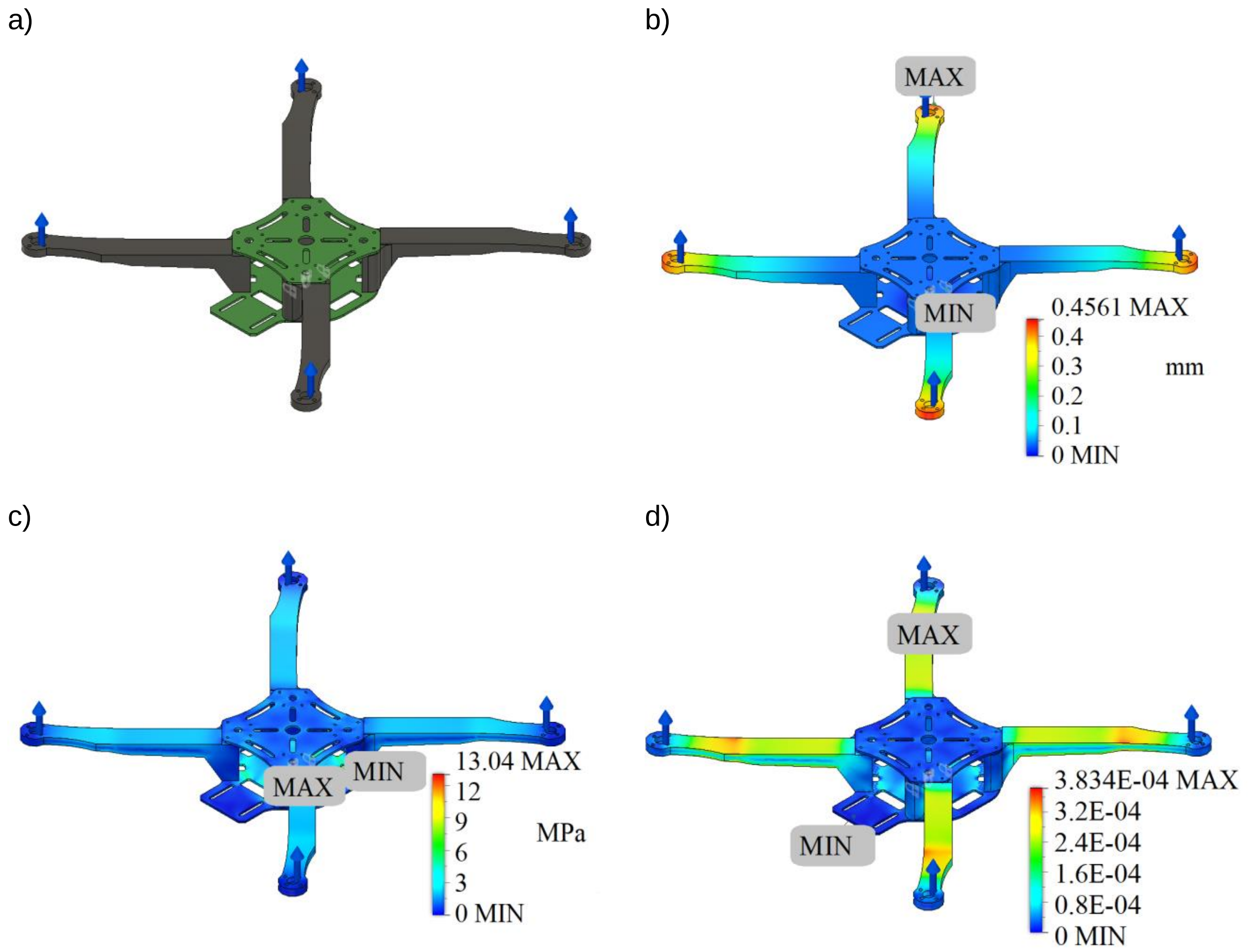
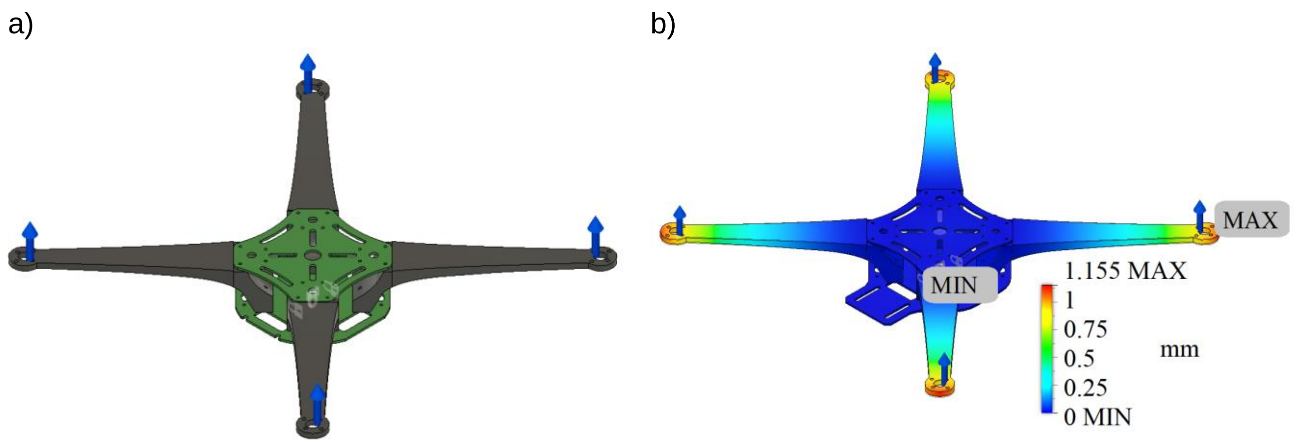


Figure 13 – Results for DJI F450 003 after optimization: a) second static analysis setup b) total displacement, c) stress distribution, d) strain distribution

The last presented model (Figure 14a) unfortunately does not meet the requirement for mass reduction. The overall weight of this variant is 0.618 kg, which is almost double the intended mass. The high mass of the arm is due to the amount of material retained at the root of the arm. Analyzing the static analysis results, it is evident that the maximum displacement has decreased, albeit only slightly, which is unexpected based on previous outputs (Figure 14b). In this case, the stress has decreased by half, whereas in both previous cases, it was nearly the same as in the original model (Figure 14c). Additionally, the highest concentration of strain at the midpoint of the arms has decreased by more than 60% (Figure 14d).



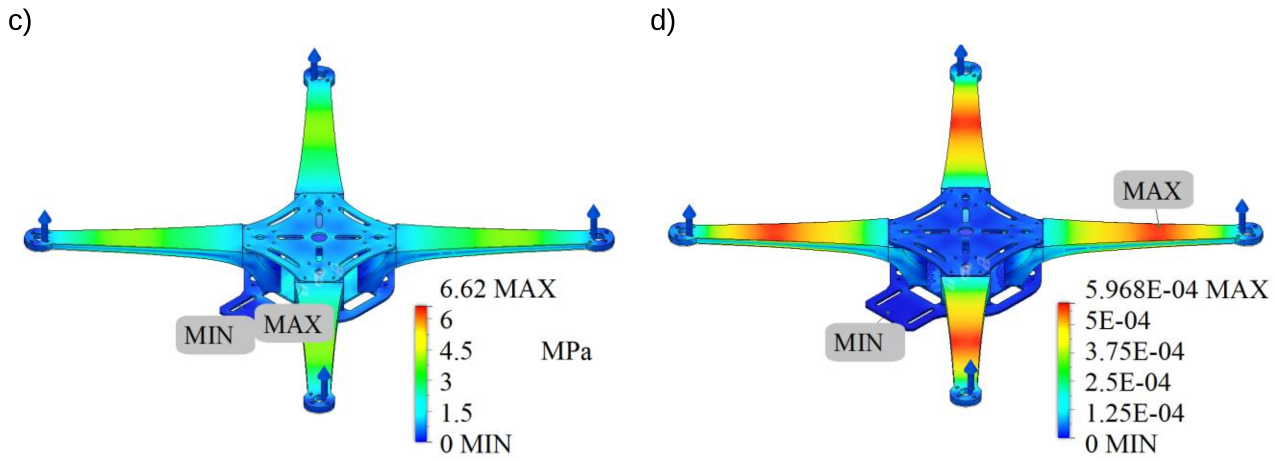


Figure 14 – Results for DJI F450 004 after optimization: a) second static analysis setup b) total displacement, c) stress distribution, d) strain distribution

The summary of second static analysis is presented in Table 6.

Table 6 – Parameters of optimized designs and second static analysis results

Parameter	DJI F450 002	DJI F450 003	DJI F450 004
mass	0.296 kg	1.028 kg	0.618 kg
volume	176 cm^3	3797 cm^3	411 cm^3
percent volume of reference	87%	1870%	202%
percent mass of reference	89%	309%	186%
Maximum von Misses stress	13.9 MPa	13.04 MPa	6.62 MPa
Maximum Displacement	0.8511 mm	0.4561 mm	1.155 mm
Maximum Strain	$7.35 \cdot 10^{-4}$	$3.83 \cdot 10^{-4}$	$5.96 \cdot 10^{-4}$

3.3 Generative design output

The goal of this analysis was to identify new design possibilities to reduce the overall weight of the drone and enhance performance, particularly in terms of the thrust-to-weight ratio. After conducting the generative design process, 56 different designs were proposed. To eliminate incomplete outputs, only those that converged were considered. Some designs failed to meet the requirements, and unfortunately, 28 of the proposed designs did not converge according to the specified criteria. This lack of convergence may have been caused by the separation of certain components or other unknown factors. All results are presented in the plot (Figure 15), which illustrates the geometries obtained in terms of mass, minimum safety factor, and the materials used.

It can be observed that designs made from PA66-GF have a significantly higher safety factor compared to other materials. However, both ABS and PA12 also show strong results in terms of minimum safety factor. The mass of PA66-GF designs ranges from 0.260 kg to 0.477 kg, whereas the masses of PA12 and ABS designs are mostly around 0.370 kg. Notably, two PA12 designs have an impressive mass of just 0.260 kg. The results presented in the graph (Figure 15) were approximate. After exporting given designs, in some cases they differed. After conducting additional analyses, two designs (outcome 11 from ABS and outcome 3 from PA66-GF) were selected as the best candidates for further static analyses.

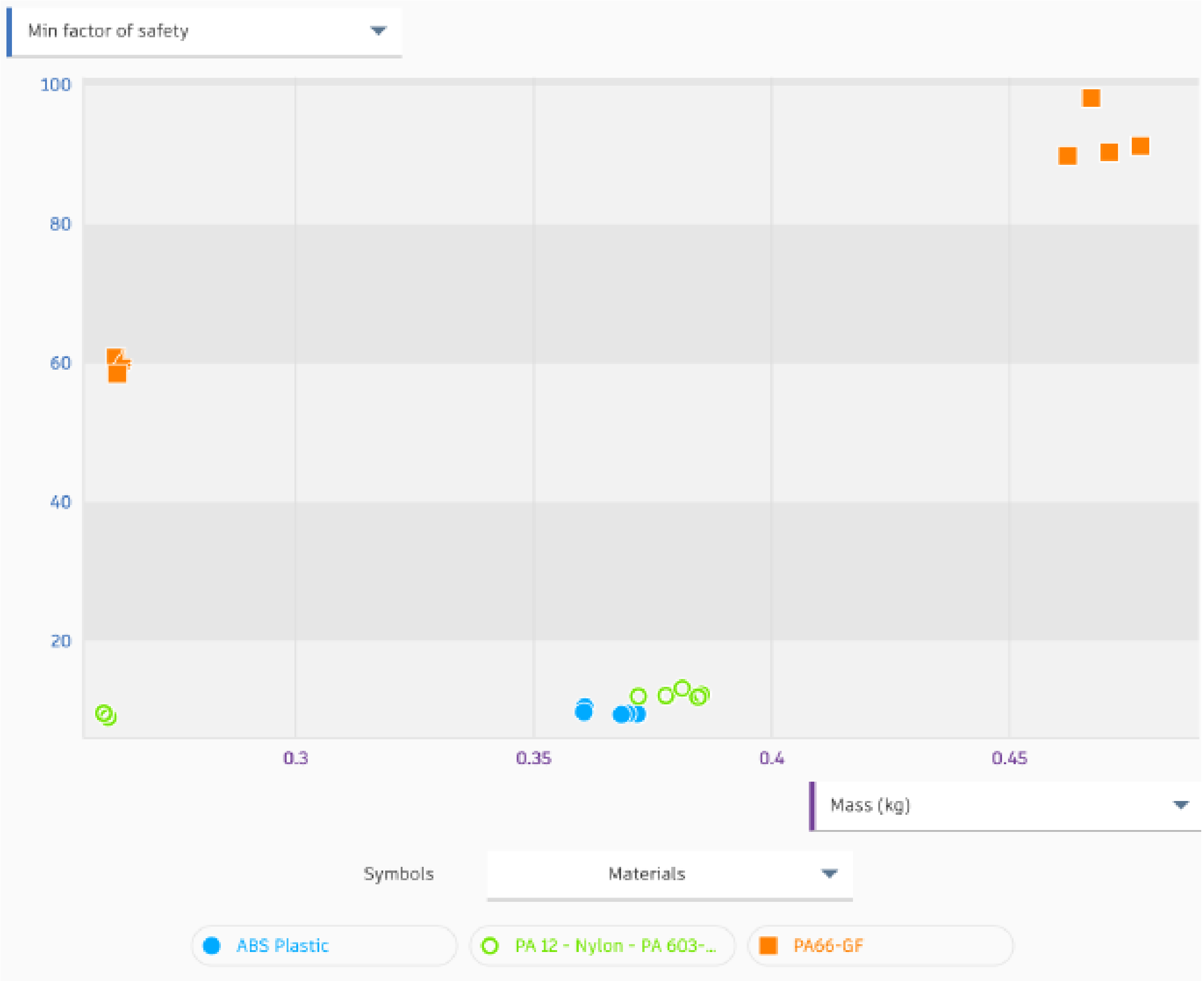
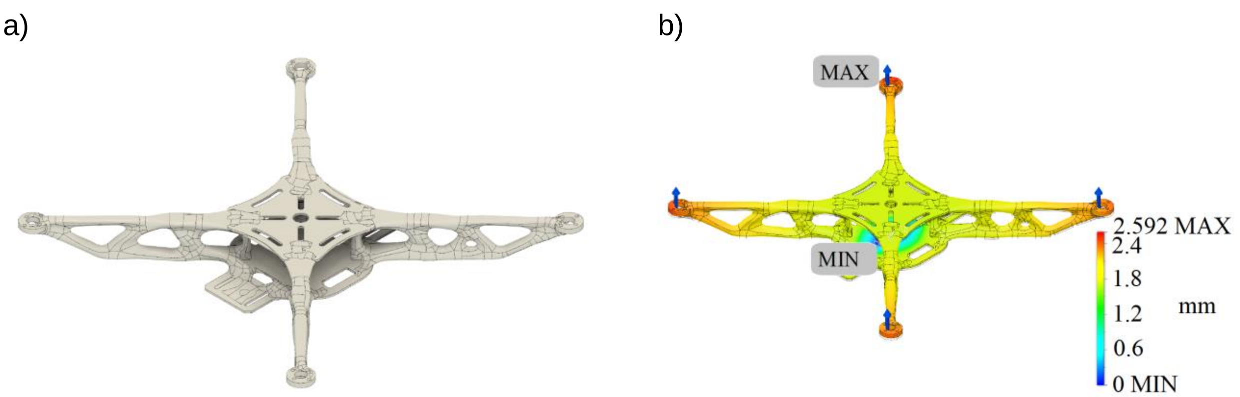


Figure 15 - The output geometries are presented on the plot, showing their mass and corresponding safety factor

3.4 Static analysis after generative design

Examining outcome 11, we observe an organic structure with four individual arms (Figure 16a). This design achieves a mass reduction of 62 grams, representing an 18.6% decrease. However, this positive result comes with increased stress (Figure 16c) and strain (Figure 16d), particularly in the drone's bottom plate. The cost of having this lighter frame is a higher maximum displacement, which is twice that of the reference model (Figure 16b).



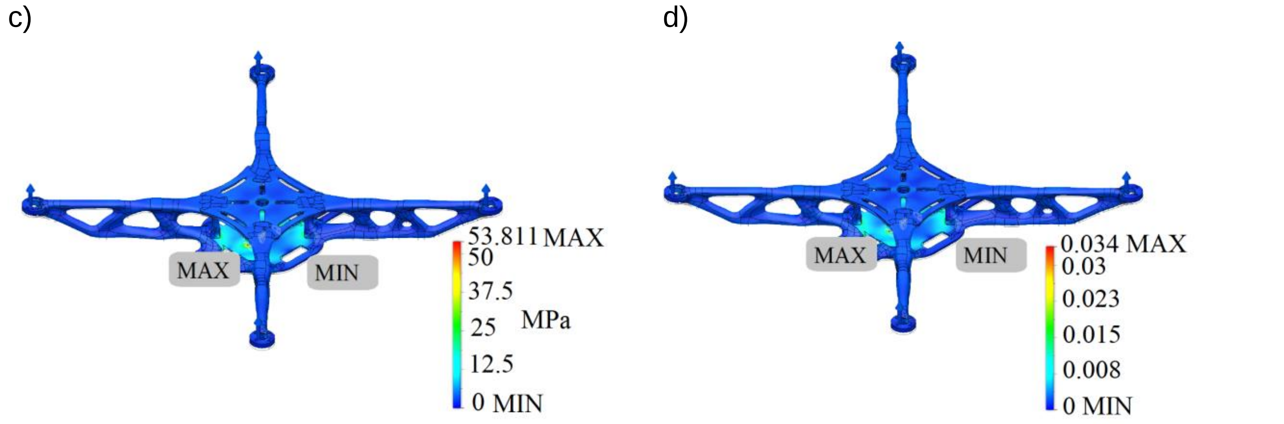


Figure 16 - Results for outcome 11: a) model, b) total displacement, c) stress distribution, d) strain distribution

In the second outcome, instead of four individual arms, the arms are connected by additional material in an organic structure (Figure 17a). This design achieves an 11.4% reduction in mass. Made from a different material, this outcome shows a lower total displacement compared to the original model (Figure 17b). However, both stress and strain are significantly higher than in the initial frame (Figures 17c and 17d). Despite this, the safety factor remains within an acceptable range (Table 7). The static analysis reveals a non-symmetrical distribution, but after adjusting the forces acting on the engine mounts and constraints, minor improvements were noted, though the overall distribution remained largely unchanged.

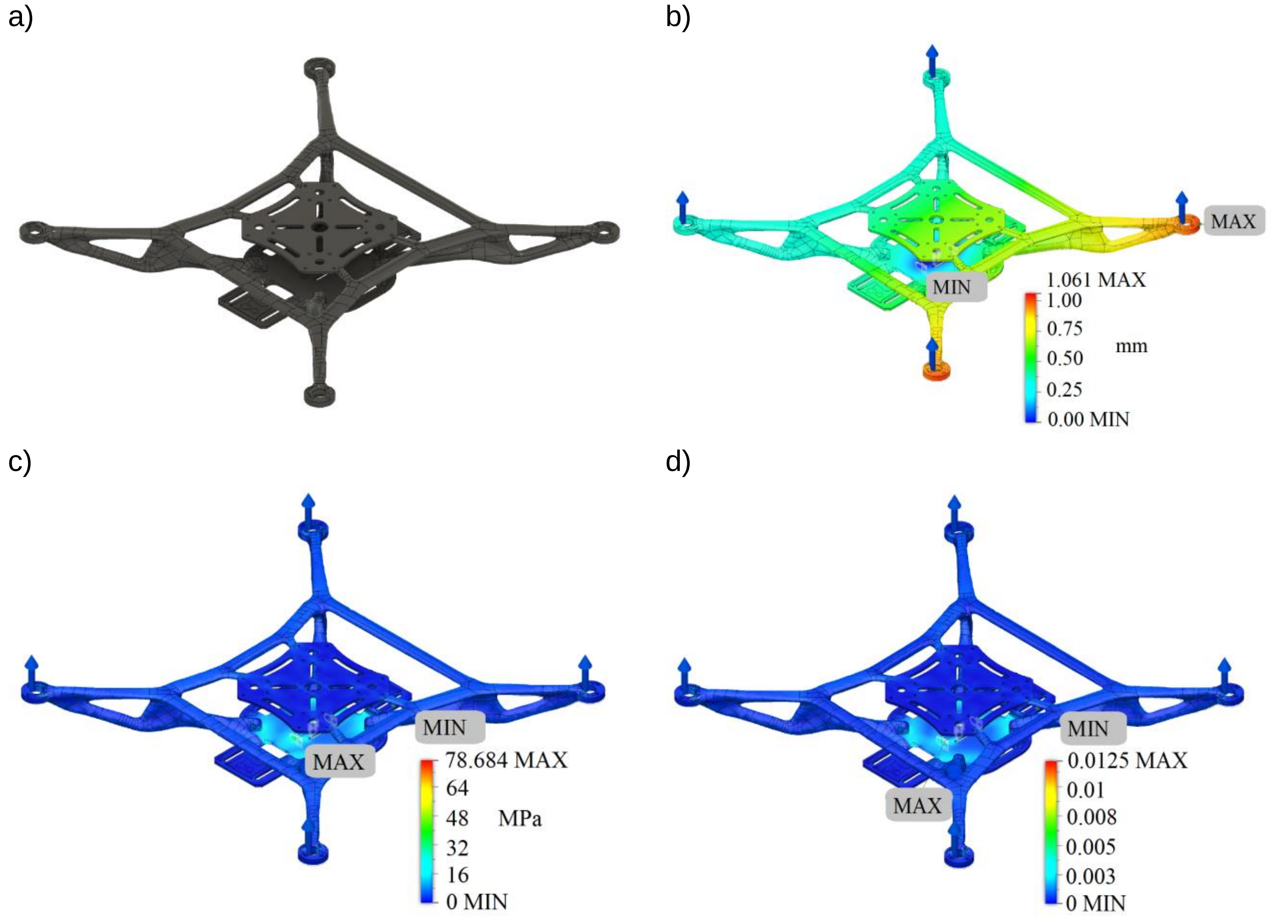


Figure 17 - Results for outcome 3: a) model, b) total displacement, c) stress distribution, d) strain distribution

The summary of static analysis after generative design process is presented in Table 7.

Table 7 – Parameters of chosen generative design outputs and static analysis results

Parameter	Outcome 11	Outcome 3
mass	$0.271\ \mathrm{kg}$	$0.295\ \mathrm{kg}$
volume	$256\ \mathrm{cm}^3$	$216\ \mathrm{cm}^3$
Maximum von Misses stress	$53.8\ \mathrm{MPa}$	$78.7\ \mathrm{MPa}$
Maximum Displacement	$2.592\ \mathrm{mm}$	$1.061\mathrm{mm}$
Maximum Strain	$3.4 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$

After completing all analyses, it can be concluded that the best models from two optimization methods are the DJI F450 002 and Outcome 11.

4. Discussion

When comparing the two optimization methods used, it can be concluded that generative design offers significantly more freedom in generating outputs. Its results showcase remarkable, diverse structures that would be difficult for a human to conceive. On the other hand, topology optimization is more constrained, as it works within predefined material boundaries, removing excess material within these limits. This results in more straightforward and natural-looking designs. Both methods share the same goal: to create the best model that meets custom requirements. Regardless of the output's shape, performance is the key factor. Both methods provide new frames with improved properties.

The process of preparing new frames differs between these methods. In topology optimization, models need to start larger or with more material, allowing the algorithm to remove what is unnecessary. In this thesis, the initial model had to be modified to include additional material. Conversely, in generative design, the approach is the opposite. The only inputs required are the geometries to be preserved and the areas where material should not be added. Generative design then automatically adds material to meet the requirements based on the constraints provided.

In topology optimization, the results serve more as guidance for how to modify the frame to achieve better performance, requiring additional post-processing. Comparing the pre-optimized and final models reveals noticeable differences. Generative design, however, produces several ready-to-use models, many of which do not require further work. While some of the generative design results may not converge or meet the requirements, about half of the outcomes are usable directly without modification.

In terms of time consumption, topology optimization is more time-intensive. It requires model preparation, running each case individually, and further modifying and checking the models. Generative design, in contrast, is much quicker. The output generation process, in particular, is more efficient—after defining constraints, manufacturing methods, and materials, the simulation is ready to run. Multiple configurations can be generated simultaneously, making the process faster and more user-friendly.

When comparing the results, generative design excels in producing models with lower masses and offering a wider range of materials. Topology optimization, however, performs better in terms of reducing stress and strain in the new frames. Additionally, topology optimization yields simpler designs, which are often easier to manufacture, whereas the organic structures produced by generative design are mostly suited for additive manufacturing.

Both methods have their pros and cons and are useful in different scenarios. However, using both approaches together provides a more comprehensive understanding of the problem at hand. Each optimization method can yield a solution that meets the necessary requirements, providing valuable insights and results tailored to the specific needs of the project.

The next step should be to implement multidisciplinary optimization in aircraft design, focusing on aerodynamics, stability, materials, structural analysis, avionics, and other key factors. This approach will advance both the design process and the broader field of air transport by integrating technical and economic aspects [17,18].

5. Conclusion

This study presents the entire optimization process, from selecting objectives to preparing models, running optimization algorithms, choosing appropriate results, modifying the models, and comparing them to the initial design. The use of two optimization methods highlights the diverse approaches to solving this problem, demonstrating that only a few outputs may meet the specific requirements. However, this approach opens new possibilities for UAV frame design, aiming for greater performance.

As shown in the analysis, only one output from topology optimization achieved a reduction in mass. On the other hand, many of the generative design outputs met the requirements, but only two were selected for detailed comparison. These selected models feature organic structures, which are challenging to manufacture using traditional methods. However, with new technologies like additive manufacturing, they can be produced.

The static analysis of the reference DJI F450 frame, alongside the optimized frames, shows that the optimized designs achieved both a reduction in maximum displacement and overall mass. The initial goal of reducing the drone frame's mass by 10% was successfully met. Additionally, the optimized frames maintain a very good safety factor and an acceptable stress-strain distribution.

Comparing the two optimization methods reveals key differences in preparation and post-processing. Topology optimization requires more effort to produce a usable result, but the outputs are often more practical and easier to implement without the need for advanced manufacturing techniques. In contrast, generative design provides a wide array of aesthetically pleasing organic structures with excellent results, but most would be difficult to manufacture or scale up using conventional methods.

Optimization models introduce a new approach, offering hundreds of potential solutions to a single engineering problem. Each solution comes with unique features and could serve different applications. Optimization in engineering not only helps solve various challenges but also improves existing solutions, driving continuous development of better designs for the world around us.

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7. Copyright Statement

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